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Dynamical and Cloud-Radiation Feedbacks in El Niño and Greenhouse Warming

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Abstract. An El Niño-like steady response is found in a greenhouse warming simulation resulting from coupled ocean-atmosphere dynamical feedbacks similar to those producing the present-day El Niños. There is a strong negative cloud-radiation feedback on the sea surface temperature (SST) anomaly associated with this enhanced eastern equatorial Pacific warm pattern. However, this negative feedback is overwhelmed by the positive dynamical feedbacks and cannot diminish the sensitivity of the tropical SST to enhanced greenhouse gas concentrations. The enhanced eastern-Pacific warming in the coupled ocean-atmosphere system suggests that coupled dynamics can strengthen this sensitivity.

1. Introduction

The tropical Pacific basin features a unique climate system with the largest body of warm surface water on the earth found in its west, a strong equatorial cold-tongue in its east, and the well known El Niño / Southern Oscillation (ENSO) phenomenon. Both the warm-pool / cold-tongue state and ENSO are produced by the same coupled dynamics (Dijkstra and Neelin, 1995; Jin, 1996). The potential importance of the coupled dynamics in the climate response to external forcing such as greenhouse warming has been recognized in recent years. A dynamical thermostat was postulated to provide a regulating mechanism for the warm pool SST and to reduce the tropical warming (Sun and Liu, 1996; Cane et al., 1997). However, coupled general circulation models (GCM) of the latest generation consistently simulate a 2-4°C warming of tropical SST when forced with enhanced greenhouse gas concentrations. Most model simulations even show enhanced eastern equatorial Pacific warming with El Niño-like SST response patterns (Tett, 1995; Meehl and Washington, 1996; Knutson and Manabe, 1998, Roeckner et al. 1999); the few exceptions show a reduced eastern equatorial Pacific warming (Noda et al. 1999). These results generally imply that the tropical coupled dynamics may not serve as a thermostat mechanism. The significant warming simulated for the tropical oceans also contradicts thermodynamical thermostat hypotheses, particularly, the so-called cloud-thermostat hypothesis inferred from the negative correlation between changes in the solar radiation flux induced by clouds and the SST during ENSO extremes (Ramanathan and Collins, 1991). The latter hypothesis was questioned widely (Fu et al., 1992; Wallace, 1992).

The intensity of tropical warming is of fundamental importance to global climate change. A better understanding of the roles of the coupled dynamical and cloud-radiation feedbacks in the tropical warming is essential for assessing greenhouse warming. In this report, we examine this issue both conceptually and quantitatively with the aid of a state-of-the-art global coupled ocean-atmosphere-sea ice model.

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2. Simulated coupled dynamic and cloud-radiation feedbacks

A number of experiments were performed with the model. We will focus on a transient greenhouse warming simulation (Oberhuber et al. 1998) in which the model was forced by increased levels of greenhouse gases as observed (1860-1990) and according to IPCC scenario IS92a for the period

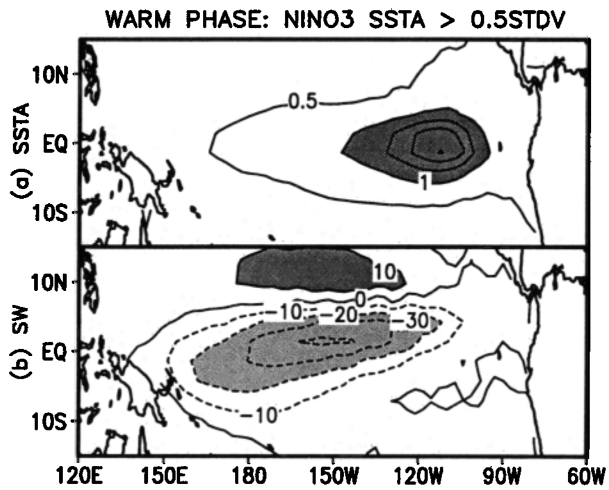

Figure 1. Composites for the model-simulated El Niños with the detrended Nino3 index (average SST anomalies in the domain of 5°N to 5°S and from 160° E to 120°W) greater than its 0.5 standard deviation. (a) SST anomaly, (b) the net surface flux anomaly of the solar radiation. The contour intervals are 0.5°C and 10 W/m, respectively.

1990-2100 (IPCC, 1992). In this simulation, there is an increased ENSO variance for the 21st century (Timmermann et al. 1999), but the main features of ENSO are not fundamentally altered. Thus, the El Niño events in this simulation are used to depict the association of solar radiative flux with the anomalous SST (Fig. 1). The simulated SST anomaly pattern is similar to the observations except that the amplitude in the central Pacific is slightly too weak. Nearly 90% of the reduced solar radiation at the ocean's surface in the central Pacific is due to the increase of cloud shielding. The remainder is attributed to the increase of water vapor content (not shown). Similar to the results of an uncoupled simulation using the atmospheric component of the model forced by observed SSTs (Chen and Roeckner, 1996), the strong negative feedback on SST in the central equatorial Pacific during the El Niños is successfully simulated in the fully coupled model (Fig. 1b). At the warming extremes of ENSO, the magnitude of this feedback in the central Pacific is above 30 $W/m^2/K$, slightly stronger than the 20-25 $W/m^2/K$ derived from observations (Ramanathan and Collins, 1991). Over the central to western Pacific, the reduction in the solar radiation due to clouds plays a dominating role in diminishing the SST anomalies.

However, this strong negative feedback associated with ENSO is dictated by the coupled dynamics of ENSO. It is the coupled dynamical instability that is responsible for ENSO in the first place (Jin, 1996). The positive feedback of tropical ocean-atmosphere interactions amplifies SST perturbations in the cold tongue to sustain either a warm or a cold phase of ENSO. On the one hand, the easterly trade winds force the thermocline depth, representing the layer of sharp vertical temperature gradients that separates the upper ocean from the abyssal deep ocean, to be shallower in the equatorial eastern Pacific than in the western Pacific. The trade winds also induce the equatorial Ekman upwelling associated with the Coriolis effects, which effectively brings cold water from the subsurface to the surface layer to generate a cold tongue in the eastern Pacific. On the other hand, the atmospheric zonal pressure gradient caused by the east-west contrast in SST drives an equatorial zonally asymmetric circulation (Walker circulation), which enhances the surface

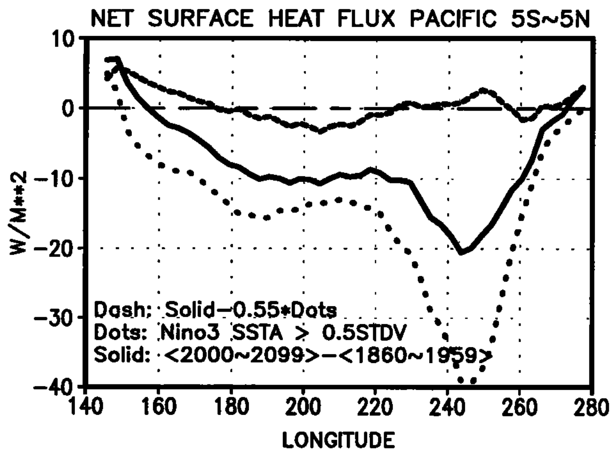

Figure. 3. Anomalous net surface heat fluxes over Pacific averaged between 5°N to 5°S. Solid, dot, and dash lines represent results from the differences between 2000-2099 and 1860-1959, the composite for the simulated El Niños with the Nino3 index > 0.5 standard deviation, and the residual difference of the above two with the later multiplied by 0.55. The units are W/m^2.

easterlies over the Pacific basin and thus strengthens the cold tongue. The strong negative cloud-radiation feedback in ENSO is a part of the coupled atmosphere-ocean interaction. The increased cloudiness in the central Pacific is associated with the convergence of the lower atmosphere circulation, which is induced by the SST anomaly and its gradients. In the ENSO cycle, SST anomalies are produced by the coupled dynamical instability which has overcome all the damping factors including this negative cloud-radiation feedback.

Once the coupled system which generates ENSO is perturbed by any external forcing such as enhanced greenhouse gas concentrations, it is the negative and positive feedbacks together, not just the negative cloud-radiation feedback alone, that determine the response. This response is shown in Fig. 2 as the changes in the mean state at the surface. There is a clearly recognizable El Niño-like signature in the central to eastern equatorial Pacific, but it is embedded in the relatively uniform warming throughout the tropical Pacific (Fig. 2a) and the entire tropics (not shown). The change in the net solar radiation, which is dominated by cloud-radiation forcing, varies from -10 W/m^2 to over -30 W/m^2 in the equatorial region. It has a distinct pattern (Fig. 2b) with the largest amplitudes narrowly trapped near the equator in the central Pacific. This pattern bears great similarity to that associated with present-day El Niño extremes (Fig. 1b).

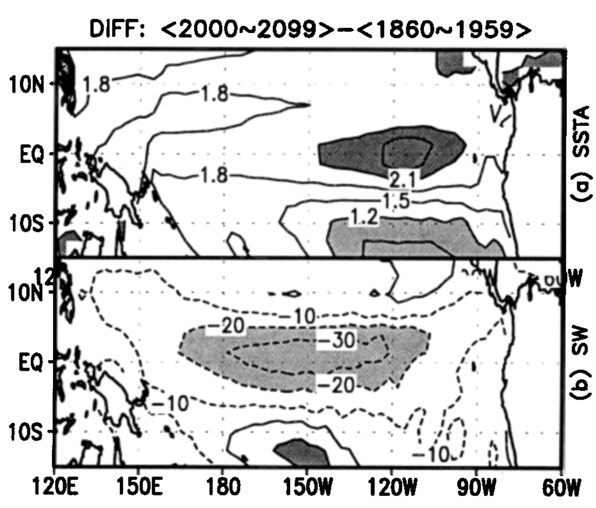

Figure 2. The same fields as in Fig. 1, but for the differences between time means for 2000 to 2099 and for 1860 to 1959. The contour intervals are 0.3°C and 10 W/m^2, respectively.

3. Estimation of the ENSO-like response in the greenhouse warming

To quantify the contribution of the forced El Niño-like response in the greenhouse warming simulation, we will consider the surface-layer energy budget. During the El- Niño mature phase (6 month average about the peak warming), the tendency of the SST anomaly is negligible (i.e. $\partial T / \partial t \approx 0$). Thus the change in the net surface heat flux (ΔH_E) will balance the change in the ocean dynamical and diffusive transports (ΔD_E) or $\Delta H_E + \Delta D_E \approx 0$. This kind of energy balance holds even more precisely for the long-term

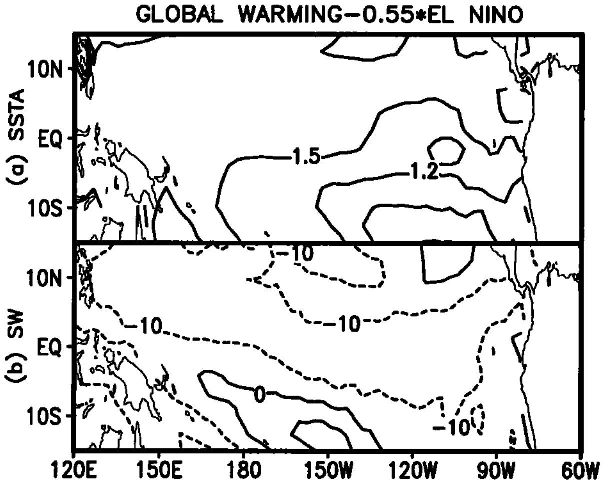

Figure 4. The same fields as Fig. 2, except for the residual difference of the results in Fig. 2 minus that of Fig. 1 multiplied by the factor 0.55. The contour intervals are the same as Fig. 2.

mean state of the greenhouse warming simulation. Using subscript T to indicate the similar terms for this case, we have $\Delta H_T + \Delta D_T \approx 0$. As inferred from the net surface heat fluxes, there are considerable contributions from the ocean dynamics concentrated largely to the equatorial upwelling zone in both ΔD_E and ΔD_T. They are also very similar in their longitudinal distributions (Fig. 3). Because ΔD_E measures the contribution of the coupled dynamics to the SST changes in the ENSO warm phase, it is reasonable to assume that similar features in ΔD_T also result from the coupled dynamics. To get a quantitative estimation, we minimize the variance of the quantity $\Delta D_T - \lambda \Delta D_E$ within 5°N to 5°S throughout the equatorial Pacific. The residual $\Delta D_T^* = -\Delta D_T + \lambda \Delta D_E$ plotted in Fig. 3 is nearly zero for λ about 0.55.

This factor λ is assumed to be the measure of contributions in the greenhouse warming coming from the El Niño-like steady response due to the coupled dynamics. We thus obtain the residual of the response in the tropics by subtructing the fields in Fig. 2 and Fig. 1, with the latter being multiplied by the value of λ. In this residual response (Fig. 4), the centers of the net surface solar radiation in the central equatorial Pacific disappear. The magnitude of the negative cloud radiation feedback in the tropical Pacific is now of the order of 5 W/m^2/K, only a small fraction of what is associated with ENSO. This gives a quantitative estimate of the model-simulated cloud-radiation feedback that is not controlled by the coupled dynamic instability. This weak feedback cannot serve as a strong thermostat to diminish SST changes in the tropics. The strong negative cloud-radiation feedback associated with the El Niño-like SST anomaly is overcome by the positive dynamical feedbacks and clearly cannot be viewed as a brake to arrest the tropical SST warming. Moreover, the model-simulated latent heat flux feedback is also very weak (not shown). Since there are no other strong negative feedbacks, the model simulates significant tropical SST increases under enhanced greenhouse gas concentrations.

In fact, the changes in mean state in this transient greenhouse warming simulation follow steadily with the greenhouse gas concentrations. The difference of the mean states averaged over the periods of year 2000-2049 and 1900-1949 is nearly the same as that over the periods of year 2050-2099 and 2000-2049. The patterns of the tropical SST and associated heat flux changes over these two contrasting episodes are essentially the same as shown in Fig. 2, while their amplitudes are about 3/4 of that in Fig. 2. Both the El Niño-like coupled dynamical response and the nearly zonal uniform response without the contribution of coupled dynamics are intensified following the accelerating enhancement of the greenhouse gas concentrations. By the end of the simulation, the steadily strengthened El Niño-like response is reaching the average El Niño amplitude of the model simulation. There is no indication yet that the simulated tropical warming is reaching a saturation level.

To verify the separation of the El Niño-like coupled dynamic response from the greenhouse warming, we further analyze a doubled CO_2 experiment with the ocean component being replaced by a fixed-depth (50 m) slab mixed layer model. Indeed, the results in the equatorial Pacific, as shown Fig. 5, are very similar to those in Fig. 4 of the scenario simulation with the El Niño-like coupled dynamical response removed. The magnitude of the negative cloud radiation feedback is again on the order of 5 W/m^2/K.

As a step forward in understanding the dynamic selection of an El Niño-like response, rather than the opposite, we further examined the greenhouse warming response without the coupled dynamical feedback. As shown in Fig. 6, there is a westerly wind anomaly in the equatorial Pacific in the doubled CO_2 experiment with a fixed-depth (50m) slab mixed layer model. This may result from the weakening of the Walker circulation due to the increase in the vertical stratification of tropical atmosphere under the forcing of enhanced greenhouse gas concentration as suggested by Knutson and Manabe (1998). To assess the possible additional SST response generated by the coupled dynamics, this wind stress anomaly was added into the Zebiak-Cane model (Zebiak and Cane, 1987) as the external dynamical forcing. An El Niño-like steady response about a half of the typical model-simulated El Niño amplitude is reproduced, which is

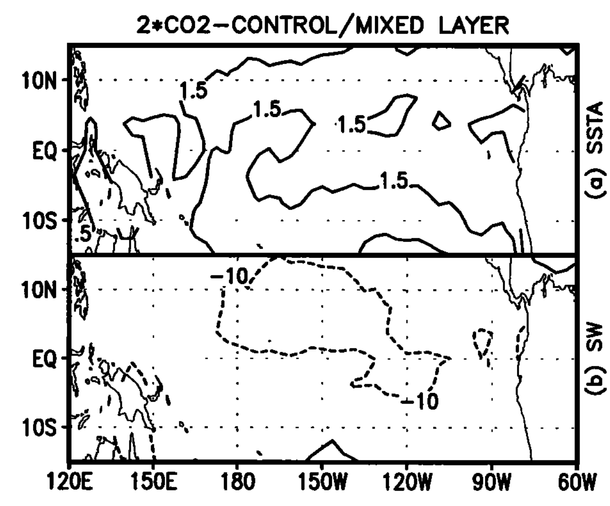

Figure 5. The same as in Fig. 2, except for the differences between the run with doubled CO_2 forcing and control run using the ECHAM4 / mixed layer model. The magnitudes have been divided by a factor of 1.75 in order to compare with those in Fig. 2 and the contour intervals are the same as Fig. 2.

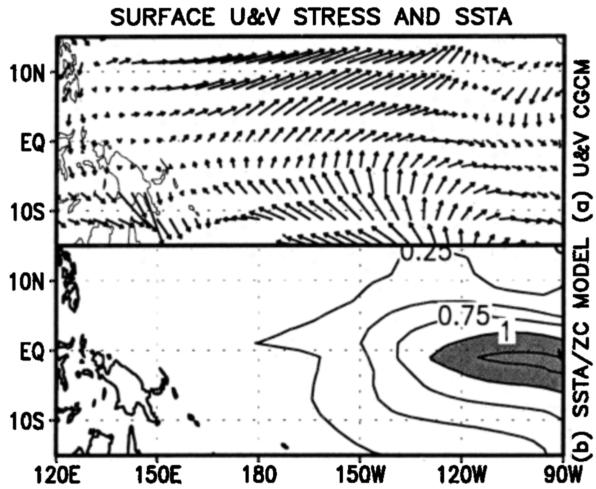

Figure 6. (a) The surface wind-stress difference between the run with doubled CO_2 forcing and control run using ECHAM4 / mixed layer model. (b) The steady SST anomaly induced by this wind-stress anomaly in a 100-year integration of Zebiak and Cane model.

consistent with our earlier estimation of λ=0.55 for the El-Niño-like response in the greenhouse warming simulation. Thus El Niño-like enhanced eastern Pacific warming in the global warming response can be attributed to the tropical coupled dynamics.

4. Conclusions

The great sensitivity of tropical SST, consistently shown in coupled GCMs in greenhouse warming simulations, is due to the lack of strong negative heat-flux feedbacks and other dynamical processes as stabilizers. Although this sensitivity may result from as yet unknown model deficiencies, the credibility of the latest generation of coupled GCMs has been significantly enhanced by virtue of their having lived up to the challenge of simulating and predicting ENSO. Model results suggest that a weak negative cloud radiation feedback may operate in the tropics but cannot stop the warming. The coupled dynamic feedbacks, which overwhelm the associated strong negative could-radiation feedback, may enhance this warming. Thus the sizable warming in the tropical SST in response to the increased greenhouse forcing is plausible.

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